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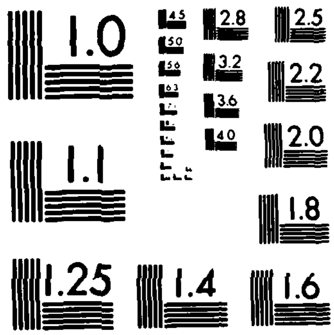

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The Effect of Strategy in Second Order Manual Control on Resource Competition with a Sternberg Memory Search Task

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This study examines the effects of two different strategies of second order manual control performance on dual-task interference using the multiple resources framework. A "response-strategy" involves discrete time-optimal double impulse control based on momentary error. A perceptual strategy involves continuous control based upon momentary error velocity. Subjects can obtain equal levels of single task performance on both tasks. Each strategy is then time-shared with a Sternberg Memory Search task,

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which uses either spatial or visual material and is displayed either auditorily or visually. Two different biases of resource allocation between the two tasks are also included. An additional manipulation was task emphasis. In different conditions subjects are requested to emphasize tracking on the Sternberg task.

The results indicated that performance using the response strategy showed a greater effect of changes in the Sternberg task code and modality than did performance using the perceptual strategy. Benefits in dual-task performance were realized with the auditory display when the double impulse, but not the continuous strategy, was employed. The effects of task emphasis were as expected with better performance observed on the emphasized task. However, no effects of Sternberg code (spatial-verbal) were observed. The results offered two interpretations: 1) The double impulse strategy actually imposes greater load on early than on late processing resources. 2) The effect of adopting perceptual or response strategies is to mobilize a pool of "general" resources to be allocated to the respective stage. Implications of the results to the secondary task measurement of operator workload are discussed.

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Abstract

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The results indicated that performance using the response strategy showed a greater effect of changes in the Sternberg task code and modality than did performance using the perceptual strategy. Benefits in dual-task performance were realized with the auditory display when the double impulse, but not the continuous strategy, was employed. The effects of task emphasis were as expected with better performance observed on the emphasized task. However, no effects of Sternberg code (spatial-verbal) were observed. The results offered two interpretations: 1) The double impulse strategy actually imposes greater load on early than on late processing resources. 2) The effect of adopting perceptual or response strategies is to mobilize a pool of "general" resources to be allocated to the respective stage. Implications of the results to the secondary task measurement of operator workload are discussed.

Introduction

The adaptability of the human operator to varying task requirements is no more discernible in any situation than that of manual control. Depending upon the control order of the specific system the human can act as a differentiator, a pure gain, an integrator or a double integrator. Generally the operator is viewed as making continuous or "smooth" control inputs into the system (Young & Meiry, 1965). However, Young and Meiry (1965) examined control situations in which a "bang-bang" or double impulse type of control input was successfully employed. Since then various researchers have also looked at control strategy. Ziegler and Chernikoff (1967) showed that familiarity with a system leads to a transition from single level to multiple level bang-bang tracking. Benjamin (1966, 1970), developing a model of a helicopter pilot, found that higher order input requirements lead to a greater tendency to use a bang-bang strategy, and that as higher order loops within the system are stabilized the bang-bang strategy is used less often.

The optimal control model of tracking considers the use of various strategies, a fundamental component of higher-order dynamic control. Wickens (1984a) argues that the selection of a strategy ("bang-bang" versus continuous) is determined by an accuracy-comfort tradeoff function. The objective of the "bang-bang" strategy is to reduce errors as soon as they occur or as rapidly as possible. For systems with second order dynamics, this translates to maximum acceleration followed by maximum braking. Clearly, this strategy is more appropriate when quick error reduction is required. An example would be provided by the task of tailing an unfriendly target during air-to-air combat. There are, however, potential costs associated with

this strategy that have to do with fuel consumption and over-correcting. Since maximum acceleration is applied to the system, the probability of overshooting is increased. In addition, imagine the case where one spacecraft must dock with another. To accomplish this in the quickest way, the operator would apply maximum thrust in one direction followed by maximum thrust in the opposite direction. This strategy would require a large consumption of fuel. An alternative strategy for this situation would be a continuous strategy; one that we shall call perceptual. With the perceptual strategy, the goal is to keep error at a minimal level by predicting the future error based on current direction and speed of the error and making continuous position adjustments in response to its momentary velocity. This strategy is referred to as a perceptual strategy because of the enhanced difficulty that humans have in perceiving higher derivatives (McRuer et al., 1968; Wickens, 1984a) It may be contrasted with the double impulse strategy in which only error positions need be perceived. The complexity of performance lies in the timing of the response. Hence, this strategy will be referred to as the response strategy.

The objectives of the present study were to examine the information processing distinctions between these two strategies of manual control within the framework of the multiple resources model of human performance. Specifically, since a major dichotomy of the model is drawn between perceptual/central processing resources (those presumably in greater demand during the perceptual strategy) and response-related resources (assumed to be most important during "bang-bang" strategies), we would expect a different impact of the two strategies upon the performance of a concurrent task.

The concurrent task selected in this study was Sternberg's Memory

Search task (Sternberg, 1974). This was chosen for three reasons: (1) because we have found the task to load heavily on perceptual/cognitive resources (Wickens, Sandry, & Vidulich, 1983), it should be suited to reflect the differential interference of the two tracking strategies; (2) because the task has often been proposed as an index of mental workload in an aviation (i.e., tracking) environment, it is important to assess how sensitive the Sternberg task is to changes in tracking demands imposed while different strategies are in effect, and while different variations of the Sternberg task are used; and (3) the use of different versions of the Sternberg task allows us to test in more detail some of the finer interactions predicted by the multiple resource model of dual task performance (Wickens, 1984b).

Using the multiple resource model of attention, four Sternberg Memory Search tasks were devised representing all possible combinations of two input modalities (visual, auditory) x two codes (verbal, spatial). The assumption was made that if the perceptual strategy of control does, in fact, require more perceptual resources than the response strategy, there should be more dual task interference (i.e., poorer dual task performance) when the perceptual strategy is employed concurrently with the perceptual-cognitive loading Sternberg task. In addition, there should be an interaction between strategy, modality of concurrent task, and code of concurrent task to the extent that interference produced by adopting the perceptual strategy would be greatest when the Sternberg task is visual-spatial in nature. Dual task performance should be worse in this condition because the resource demands of the two tasks would show the greatest overlap. Furthermore, since this condition is predicted to share the most resources between the two tasks, it should also be the condition that allows resources to

be exchanged most readily as priorities are shifted between tasks. When the Sternberg task is auditory-verbal on the other hand, there should be less interference and sharing of resources. Interactions of the type just described should presumably be smaller when tracking is performed with the response strategy.

A schematic prediction of the results is shown in Figure 1. The ordinate represents some overall measure of interference between the tracking and Sternberg tasks. This interference may be reflected in the tracking error measure, the Sternberg latency or error measure, or both, but will be enhanced in whichever task is deemphasized, as priorities are shifted between them.

The heavy line indicates the main effect of control strategy, collapsed across Sternberg tasks. Because second order tracking is more demanding than first, the two points to the right are greater than the first order point to the left. Furthermore, because the perceptual- cognitive Sternberg task is assumed to demand primarily early processing resources (Wickens, Sandry, & Vidulich, 1983), interference will be greater when the perceptual strategy is employed.

The solid line can be decomposed into the two dashed lines that represent the spatial and verbal variants of the Sternberg task. Because tracking is spatial, interference will be enhanced with the former stimuli, and more so as the perceptul strategy is employed. Finally, each of these can be decomposed further into stimulus modality differences: visual and auditory. Here again for either the spatial or verbal form, the multiple resource theory predicts that the harm of the visual modality will be enhanced with the perceptual strategy.

Method

Subjects. Eight right-handed male undergraduates at the

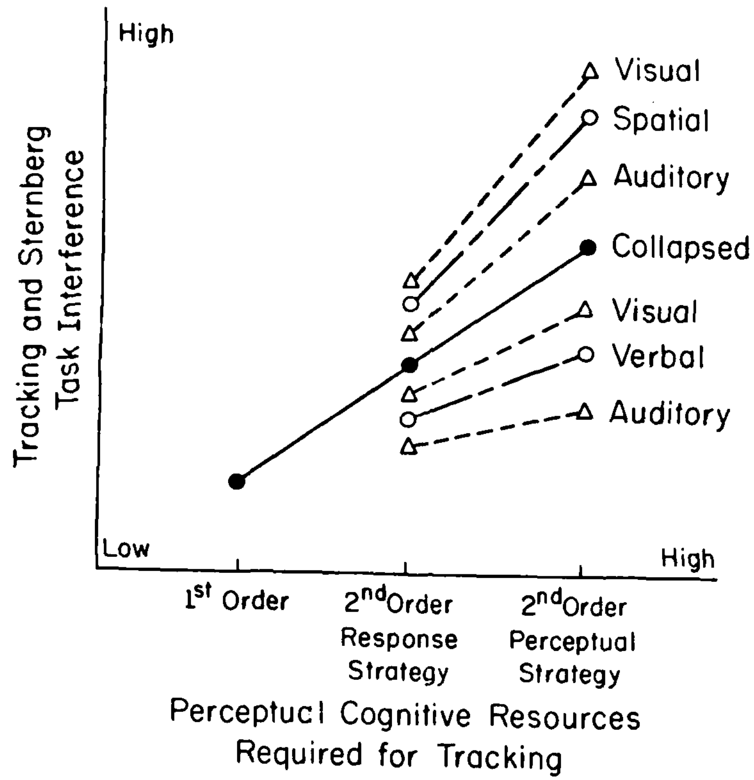

Figure 1. Predicted order of dual task interference across strategy and format conditions.

University of Illinois were recruited for this experiment. All subjects were paid $3.35 per hour.

Apparatus. Both tasks employed a PDP-11/40 computer. The computer and the video display were interfaced via a HP-3600 graphics display interface. Manual inputs from the subjects were recorded via a keyboard device for the Sternberg tasks and via a spring loaded control stick for the tracking task. A multi-tone generator was used to provide stimuli for the auditory-spatial Sternberg task. Digitized pre-recorded speech was generated and presented as stimuli for the auditory-verbal Sternberg tasks via a Centigram MIKE Voice Unit.

Tracking task. The subjects were placed in a sound and light attenuated booth approximately 75 cm from the CRT screen. Subjects were required to keep a square cursor (.5cm x .5cm) positioned on the midline of a horizontally oriented rectangle (1cm x 7.3cm). Subjects performed the task with their right hand under both first and second order control dynamics. A disturbance frequency of .32 was added to the system. The first order tracking dynamics were used as a control condition.

Sternberg tasks. Four versions of the Sternberg task were employed. Each represented one of the four modality x code combinations. Two of the tasks used a verbal format. In these tasks letters were presented either visually or auditorily. Prior to each trial, subjects were given four letters to hold in working memory. During the subsequent 3 minute trial, subjects were presented a series of probe stimuli at an interstimulus interval that ranged between 3 and 5 seconds, and were required to indicate with a button press whether a given probe stimulus was a member of the memory set.

The other two tasks were spatial in nature. The stimuli were not

letters in the alphabet, but rather a dot or a tone in a 3 x 4 matrix. In the visual version of the task, a 4 row x 3 column matrix (3 cm x 2 cm) appeared on the screen. The task was to memorize the position of 2 dots presented in the matrix and indicate whether subsequent stimuli were members of the memory set.

The auditory matrix was composed of 4 tones (250, 400, 650, 1000Hz) which could occur at three positions relative to the head (left ear, right ear, and mid-plane) generating 12 possible stimuli. Subjects were required to memorize the location (i.e., pitch and position) of 2 tones (i.e., set size of 2), and indicate whether subsequent probe tones were from the memory set.

For all four tasks subjects were asked to respond as fast and as accurately as possible. This task was performed with the left hand. Error rate and reaction time latency were recorded.

Dual tasks. For dual task configurations when the Sternberg task was visually presented, it appeared immediately (1-1.5 degrees visual angle) below the tracking display.

Procedure. Subjects participated in two (1.5 hour each) practice sessions and four (1.0 hour each) experimental sessions. There were seven single tasks: four Sternberg tasks and three tracking tasks (first order, response strategy, and perceptual strategy). In the first practice session, subjects were introduced to the seven single tasks and received practice on each one. The second practice session consisted of both single task and dual task practice. Before each dual task trial, subjects were instructed to devote equal amounts of effort on both tasks and not to emphasize one over the other.

During the four experimental sessions, subjects first performed each of the single tasks. Then subjects performed each of the twelve

dual task combinations. These were created by the orthogonal combination of the 3 tracking conditions (1st order, 2nd order perceptual, and 2nd order response), times the four Sternberg conditions. In addition, each task was replicated under different task emphasis conditions. Before each dual task trial, subjects were instructed to devote more (70%) of their effort on one of the two tasks. Between trials, subjects were given verbal feedback about their performance on the previous trial and informed about their next trial.

Strategy was manipulated through instructions. The advantages and disadvantages of the two strategies were described. In addition subjects were told that when using the response strategy, they were to emphasize quick error correction with large stick deflections (bang-bang responding). For the perceptual strategy, subjects were instructed to keep error minimal but give the cursor a 'smooth ride.' These instructions are presented in Appendix A. Before each dual task trial, subjects were told which condition would follow and were reminded what to emphasize if a strategy was required.

Design. All factors were manipulated within subjects. Bias was manipulated between sessions and alternated from session to session. Half the subjects emphasized the Sternberg tasks during sessions 1 and 3 and the tracking task during sessions 2 and 4. The other half of the subjects received the reverse order.

The presentation order of the tracking task was nested within each of the Sternberg tasks and was counterbalanced. The order of the Sternberg tasks was counterbalanced, via a Latin squares method, across the four experimental sessions. For half the subjects in each bias order, the pattern of the Sternberg tasks was reversed. Practice effects were studied by comparing the first two sessions with the

second two sessions.

Results

Single Task Analysis

Tracking task analysis. Two measures were used to evaluate tracking performance: Root Mean Square (RMS) tracking error and mean absolute control velocity. A two-way, Strategy x Practice analysis of variance was performed on each dependent variable. For RMS tracking error, no effects were reliable. For mean control velocity, there were no practice or interaction effects. However, there was a reliable and expected strategy effect on control velocity; $F(1,7) = 32.70$, $p < .001$. The mean control velocities for each strategy are presented in Table 1. The leftmost column of the table gives the data for all subjects, the middle and right columns give the data for two different subgroups that will be discussed below. This table indicates that the average velocity for the perceptual strategy is considerably smaller than that for the response strategy. These two analyses indicate that overall, subjects were able to discriminate between the two strategies and could perform the tracking task equally well using either strategy.

Sternberg task analysis. Error rate and response latency were used to evaluate performance on the Sternberg tasks. A three-way Modality x Code x Practice analysis of variance was performed on the two measures. For the latency data, only the main effects of Modality ($F(1,7) = 61.11$, $p < .001$) and Code ($F(1,7) = 9.90$, $p = .016$) were reliable. Table 1 presents the mean latencies for the four Modality x Code display formats. Overall, the latency was shorter for the visual modality and for the spatial tasks.

Error rate data are also presented in Table 1. Again the main effects of Modality ($F(1,7) = 6.63$, $p = .037$), and Code ($F(1,7) =$

Table 1

Single Task Performance Measures for All Subjects and Two Subgroups

Group		All Subjects		Perceptual Trackers		Response Trackers	
Strategy		PERC	RESP	PERC	RESP	PERC	RESP
RMS Error		342.09	316.28	340.50	353.33	343.05	299.05
Control Velocity		118.12	343.75	125.00	368.33	114.00	329.00
Group		All Subjects		Perceptual Trackers		Response Trackers	
Modality		VIS	AUD	VIS	AUD	VIS	AUD
Response Latency	Code Verbal	567.59	706.78	567.92	737.08	567.40	688.60
	Spatial	533.41	646.69	519.58	647.58	541.70	646.15
Error Rate	Verbal	4.24	4.77	2.64	5.03	5.20	4.62
	Spatial	5.105	10.64	5.59	9.45	4.81	11.36

10.43, p = .014) were reliable. In addition, the Modaltiy x Code interaction approached reliability ($F(1,7) = 3.93$, p = .088). From Table 1 we find again an advantage for the visual modality. However, the error rate for verbal tasks was lower than that for the spatially coded tasks, suggesting a slight speed-accuracy tradeoff: The spatial stimuli produced faster, but less accurate responding. When the cell means are examined more closely, it is apparent that the cause of all effects was the particularly high error rate for the auditory-spatial tasks. All other versions of the Sternberg task were about equal in difficulty.

Dual Task Analysis

Tracking performance. As previously mentioned, first order tracking conditions were included to serve as a control baseline from which to examine the processing changes entailed by coping with increased order, using the two different strategies. RMS tracking error for these first order dual task trials was subtracted from the corresponding second order conditions in which strategy was manipulated. These decrement scores are presented in Figure 2. The left half of the figure shows the tracking error data for the perceptual strategy while the right half shows the same effects for the response strategy. Within each half of the graph, the leftmost points indicate performance when tracking was time-shared with the verbal Sternberg tasks while the rightmost points are for the spatial tasks. The open circles and dashed lines indicate visual formats, and filled circles with solid lines denote auditory formats. Finally, the sloping lines running through each point indicate the effects of priorities. The higher error on the right of each line is that observed during pro-Sternberg conditions. The points in the middle of each sloping line

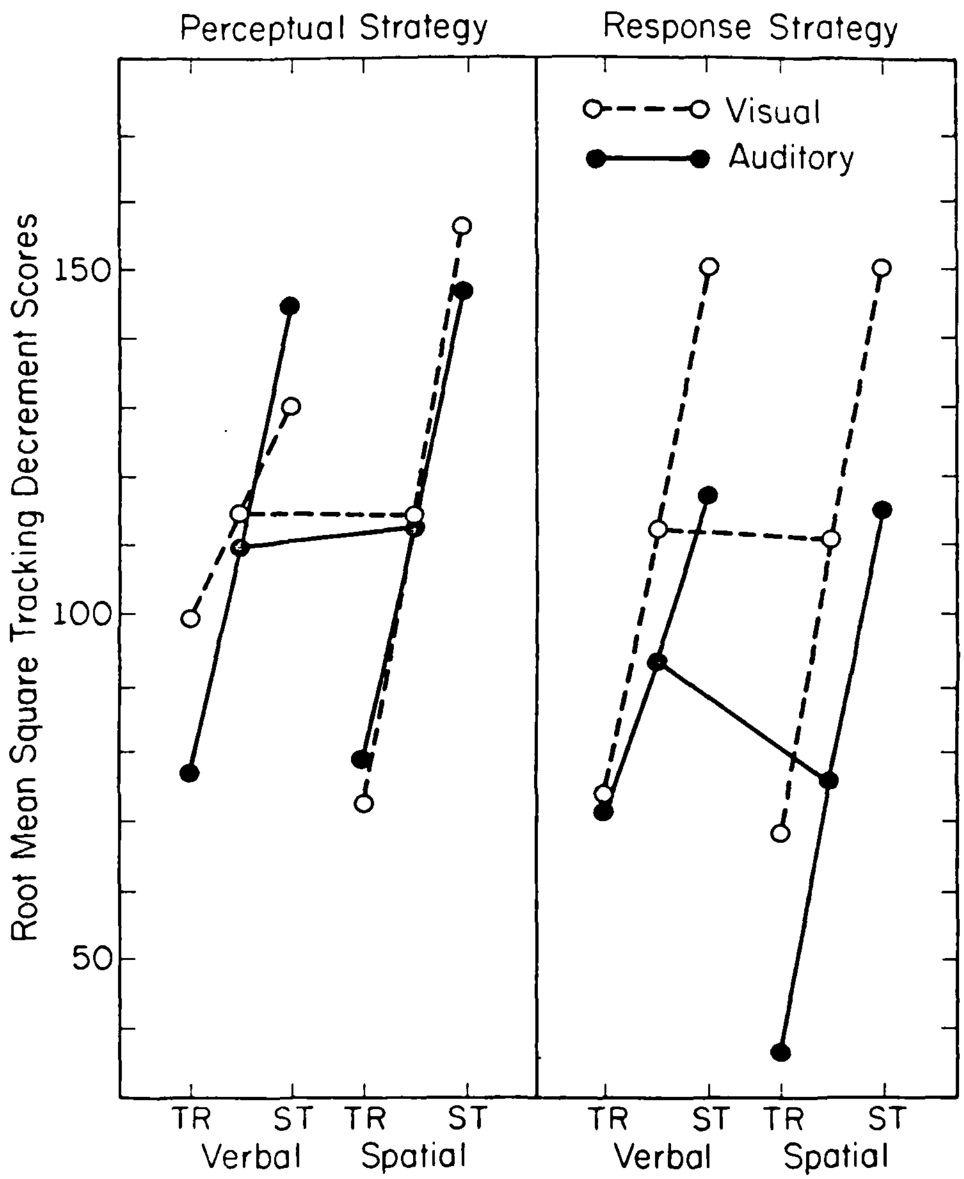

Figure 2. Effects of strategy, display format, and bias on the first-second order RMS error decrement scores (first order error is subtracted from second order error in the corresponding condition).

simply represent the mean performance of the two allocation conditions. A five-way, Modality x Code x Bias x Strategy x Practice analysis of variance was performed on the error data in Figure 2, as well as on the control velocity measure. Each of these will be discussed in turn.

RMS error. For RMS tracking error, two main effects were found to be reliable: Error was reduced with practice ($F(1,7) = 17.29$, $p = .004$) and bias influenced tracking error in the expected direction. ($F(1,7) = 29.11$, $p = .001$). The main effect of modality approached reliability ($F(1,7) = 5.03$, $p = .060$). In addition, the Modality x Strategy interaction was reliable (($F(1,7) = 6.48$, $p = .038$). Adopting a response strategy had no effect on tracking performance when the Sternberg task was displayed visually, but reduced the tracking decrement when an auditory display was used. From Figure 2 we can see the large tradeoff effect as emphasis is switched from the tracking task (TR) to the Sternberg task (ST) indicating that tracking was sensitive to the amount of resources allocated to it. The modality main effect indicated that decrement scores were smaller when the concurrent task was presented along the auditory channel. However, as suggested by Figure 2 and the modality by strategy interaction, this effect was larger when the response strategy was used. As indicated by the relative vertical position of the four 'Hs', when the perceptual strategy was used, tracking performance was about the same whether the Sternberg task shared the visual modality or was presented auditorily. When the response strategy was used, tracking was better when the Sternberg task was presented along the different (auditory) modality. This result, contrary to predictions, suggests that the auditory Sternberg task produces a relative improvement in tracking performance but only when the response strategy was used.

Control velocity. The main effect of Strategy ($F(1,7) = 37.28$, $p < .001$) was the only reliable main effect for the control velocity measure (see Table 2). The mean absolute velocity was approximately 2 1/2 times greater in the response than in the perceptual strategy condition. Two interactions, Practice x Code x Bias ($F(1,7) = 9.40$, $p = .018$), Practice x Modality x Strategy ($F(1,7) = 7.05$, $p = .033$), were also reliable.

Sternberg tasks. As with RMS error, decrement scores for the Sternberg latency measures were obtained by subtracting scores from those observed during the first order tracking conditions. In this way the data may be interpreted in terms of the _impact_ of the increase in control order on processing of different formats of discrete stimulus material. Also, error rate was measured and analyzed. Figure 3 shows the latency decrement scores for the Sternberg tasks in dual task conditions plotted in identical format to the tracking data of Figure 2. A five-way, Modality x Code x Bias x Strategy x Practice analysis of variance was performed on both task measures.

For latency, the main effect of Bias ($F(1,7) = 7.65$, $p = .028$) was reliable as it is apparent from Figure 3 that subjects were able to allocate their resources between the two tasks. When subjects were asked to devote more effort to the tracking task, latency on the concurrent Sternberg task increased, with the one notable exception evident for the auditory spatial task when the response strategy was employed. Also, the main effect of Code approached reliability ($F(1,7) = 5.26$, $p = .056$). As Figure 3 shows spatially coded tasks resulted in a smaller decrement.

Only one interaction, Modality x Bias ($F(1,7) = 13.85$, $p = .007$) was reliable. There was a larger bias effect when the tasks were

Table 2

Control Velocity. Strategy Effects for Dual Task Conditions

Perceptual	Response
138.80	334.01

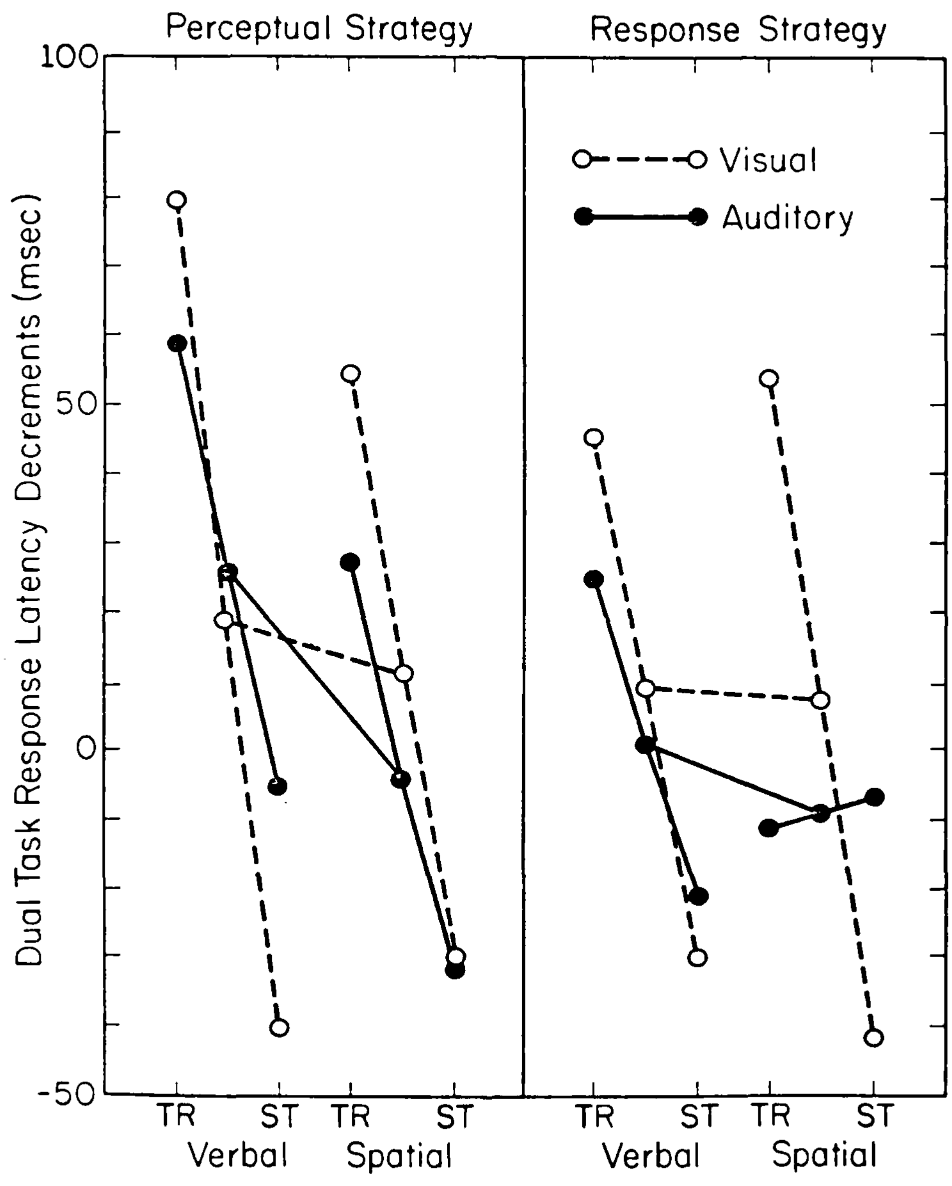

Figure 3. Effects of strategy, display format, and bias on the Sternberg Latency decrement between first and second-order tracking conditions.

presented visually. This finding is consistent with the conception of the visual modality as a resource. When tasks share one modality, as they do in the visual input condition, subjects have a greater opportunity to shift priorities (and therefore resources) between tasks than when they do not.

Finally, the Bias x Practice interaction ($F(1,7) = 4.77$, $p = .065$) and the Bias x Code x Modality x Strategy interaction ($F(1,7) = 4.82$, $p = .064$) approached significance. There was a larger practice effect when the tracking task was emphasized than when the Sternberg task was emphasized. When the tasks were well practiced, the Sternberg task became less sensitive to the addition or withdrawal of resources.

Error rate. Figure 4 gives error rate bias effects in dual tasks. The left half of the figure gives data from the first two sessions and the right half gives data from the second two sessions. The leftmost points in each half are for the verbal stimuli and rightmost points are for the spatial stimuli. Solid lines and filled points indicate auditory versions while open circles with dashed lines denote visual versions. For error rate, three main effects were reliable. It is apparent from from Figure 4 that the main effect of Modality ($F(1,7) = 24.61$, $p = .002$) indicates that the visual Sternberg tasks were performed more accurately. The main effect of Code ($F(1,7) = 5.33$, $p = .054$), depicted in Figure 4, suggests that verbally coded tasks were easier than the spatially coded tasks. Perhaps this was a result of a high familiarity with letters. The main effect of Bias ($F(1,7)= 6.64$, $p = .037$) is also presented in Figure 4. Emphasizing the tracking task generally increased the error rate on the Sternberg task and vice versa. Two interactions, Bias x Modality ($F(1,7) = 4.77$, $p = .065$) and Bias x Modality x Practice ($F(1,7) = 5.40$, $p = .053$), approached

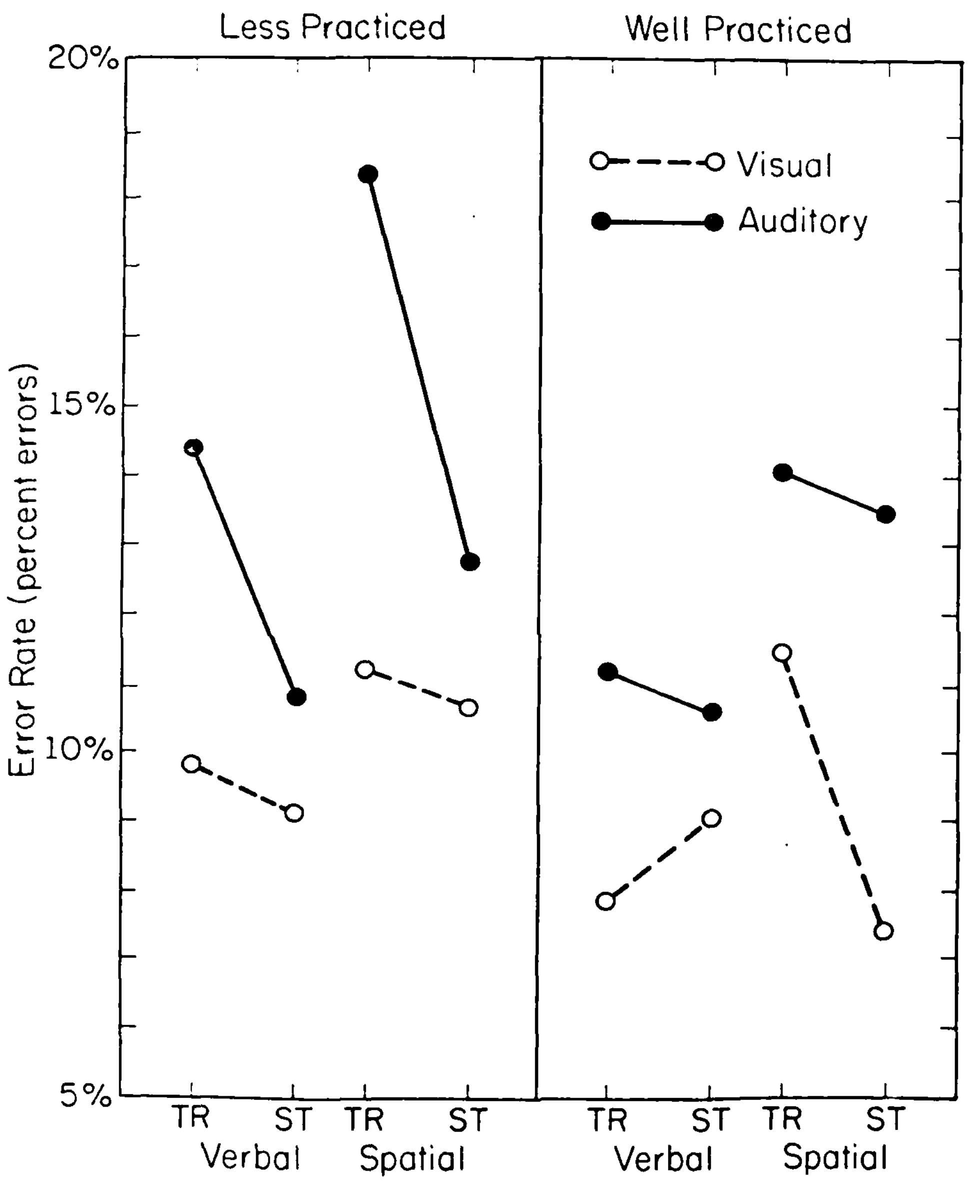

Figure 4. Effects of display format, bias, and practice on the Sternberg task error rate.

significance. When tracking was paired with an auditory task, the effect of bias was larger. However, this effect was smaller when tasks were well practiced.

Group analysis. Since the experimental manipulations tended to increase the likelihood of individual differences, the tracking performance of individual subjects was examined to identify possible differences in strategies. Although no differences in either single task tracking or reaction time were discovered (see Table 1), the dual task data suggested that the eight subjects could be divided into two distinct groups. For dual tasks, five subjects were able to perform better with the response strategy than the perceptual strategy: this group will be referred to as response trackers. Group 2 (three subjects) performed better in dual tasks when they used the perceptual strategy (perceptual trackers). The results of the group analysis are presented below.

A six-way, Modality x Code x Bias x Practice x Strategy x Group analysis of variance was performed on the four dependent measures to compare and contrast the two groups.

Figure 5 shows the Group x Strategy effects for RMS error (5a) and Response Latency (5b). For RMS data, three group effects were reliable; Strategy x Group ($F(1,6) = 13.77$, $p = .010$), Practice x Group ($F(1,6) = 12.94$, $p = .011$), and Bias x Modality x Practice x Group ($F(1,6) = 6.52$, $p = .043$). As shown in Figure 5a and b, each group tracked better and showed faster RT when using their preferred stategy. In addition, the perceptual trackers showed greater improvement with practice. Finally, when the tasks were well practiced, the perceptual trackers were less sensitive to resource addition and withdrawal when the Sternberg task was auditory. The response trackers showed less bias

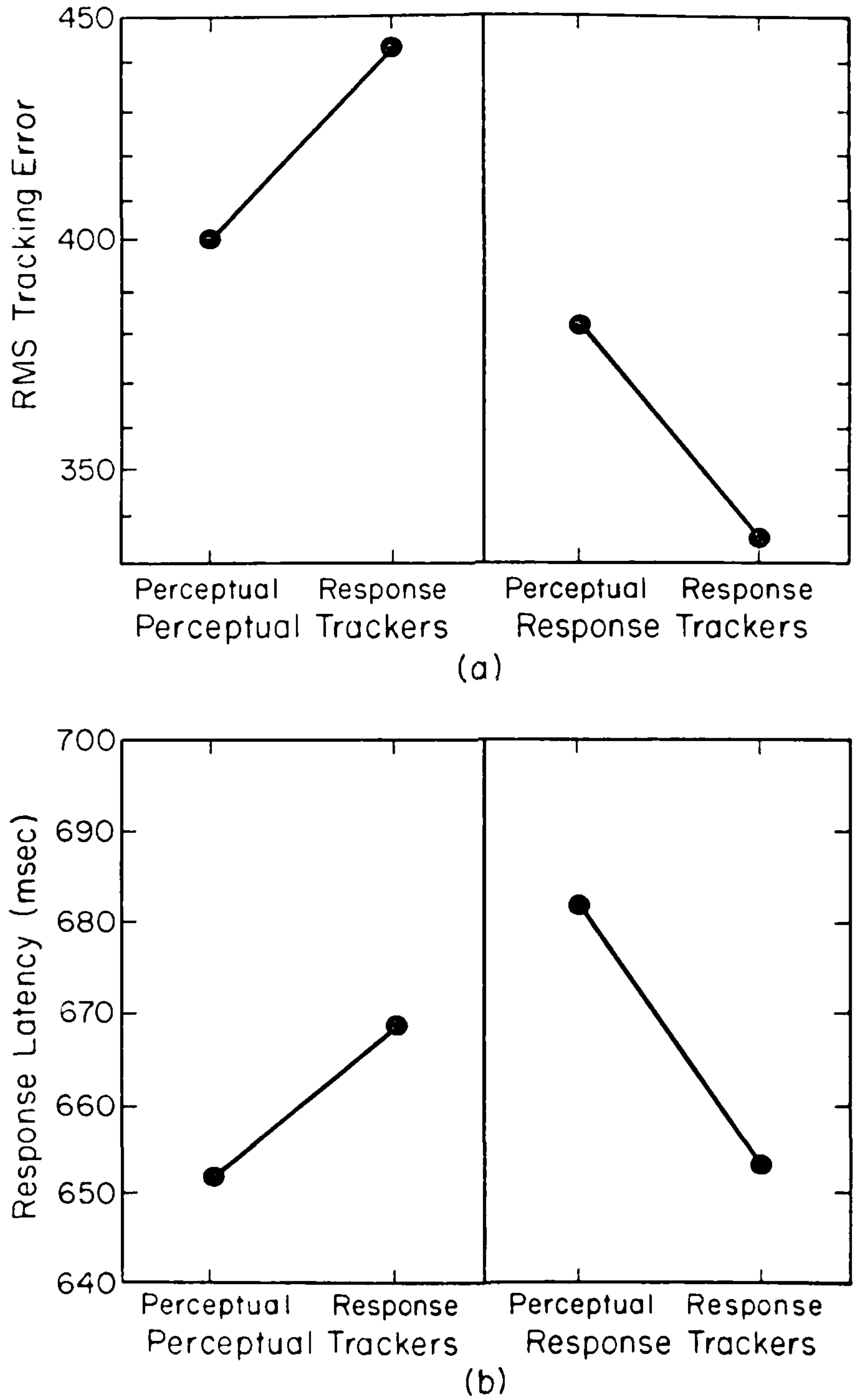

Figure 5. Second order performance data broken down for "perceptual" and "response" trackers; (a) RMS error decrements; (b) Sternberg latency decrements.

effect when the concurrent Sternberg task was visual, although the size of the effect was smaller for this group. In the unpracticed conditions the effects, though much smaller, were reversed (across modality) for both groups. These last two interactions are shown in Figure 6.

For the latency data, in addition to the previously discussed effects, the Strategy x Group effect was reliable ($F(1,6) = 13.29$, $p = .011$). When both groups were tracking with their preferred strategy, response latency in the Sternberg Task was minimal (Figure 5b).

Finally, for error rate, a number of group effects were reliable. These effects include: the main effect of Group ($F(1,6) = 6.57$, $p = .009$) and Practice x Group ($F(1,6) = 14.23$, $p = .009$). These effects indicate that (a) the response trackers were more accurate, (b) the perceptual trackers showed more improvement.

POC analysis. The effects on tracking and the Sternberg task latency that we have described thus far are not entirely consistent with each other. For example, the Sternberg task latency decrements were reduced when the spatial task was employed, while tracking error was unaffected. One of the primary goals of the investigation was to assess the joint impact on performance of both tasks as a function of their concurrence. It is often difficult to ascertain this mutual interference by examining individual performance decrements separately. In Figure 7, the joint performance decrements have been represented in the Performance Operating Characteristic or POC space, in which performance on the tracking task increases across the horizontal axis and performance on the Sternberg task increases up the vertical axis. The two points connected by each line represent the two allocation instructions. The fact that all lines are roughly oriented in the same

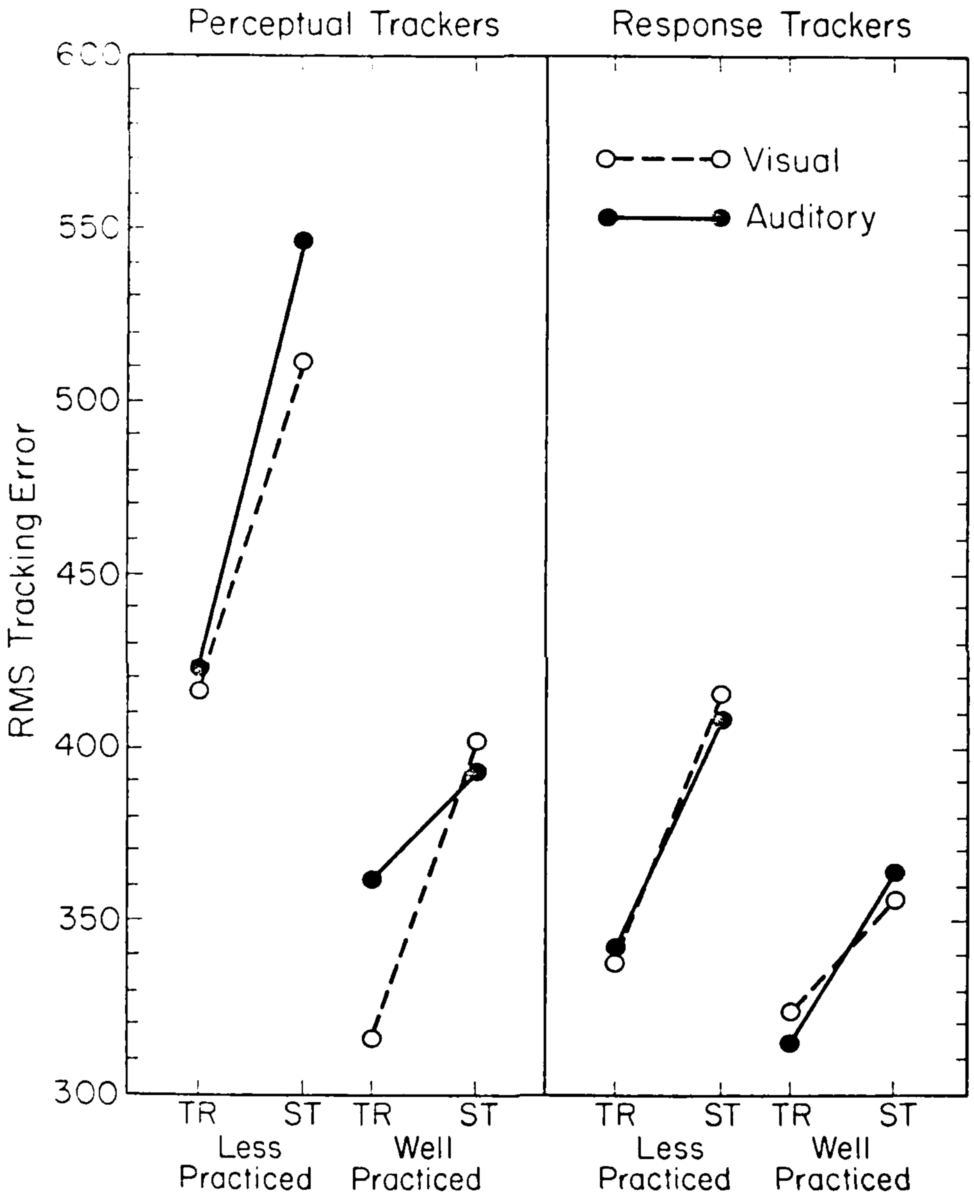

Figure 6. Tracking error data for the two tracking types, the four display formats, and the two bias levels.

direction indicates that allocation instructions were successful at improving the favored task, and reducing performance on the unfavored one. The panel on the top (7a) indicates the tradeoff when the perceptual strategy was employed. That on the bottom (7b) indicates performance with the response strategy. Within each panel the four lines are coded by their corresponding combinations of display modality and code.

In interpreting data within the POC space, it is important to consider two dimensions. Movement along the positive diagonal (from lower left to upper right) represents an increase in time-sharing efficiency. Movement along the negative diagonal (from upper left to lower right) represents a shift in resource allocation policy from one favoring memory search, to one favoring tracking (Navon & Gopher, 1979; Wickens, 1984a,b). Beyond the general effect of priority allocation, it is somewhat difficult to discern strongly pronounced trends in the data of Figure 7, or to compare the data between the two strategy groups. In order to make such a comparison easier, midpoints of each line segment in Figure 7 have been identified to reflect the "average" or typical level of dual task performance. In Figure 8 these eight average values have been connected by two lines, the solid line representing performance with the response strategy, the dashed line with the perceptual strategy. The general trend with both strategies is for a montonic increase in performance to occur across the order VV, VS, AV, and AS. The primary source of this improvement is a reduction in the Sternberg decrement. The fact that time-sharing efficiency appears better with auditory than visual stimuli is expected and predicted by multiple resource theory. However, the superior performance with the spatial tasks runs counter to expectations, since

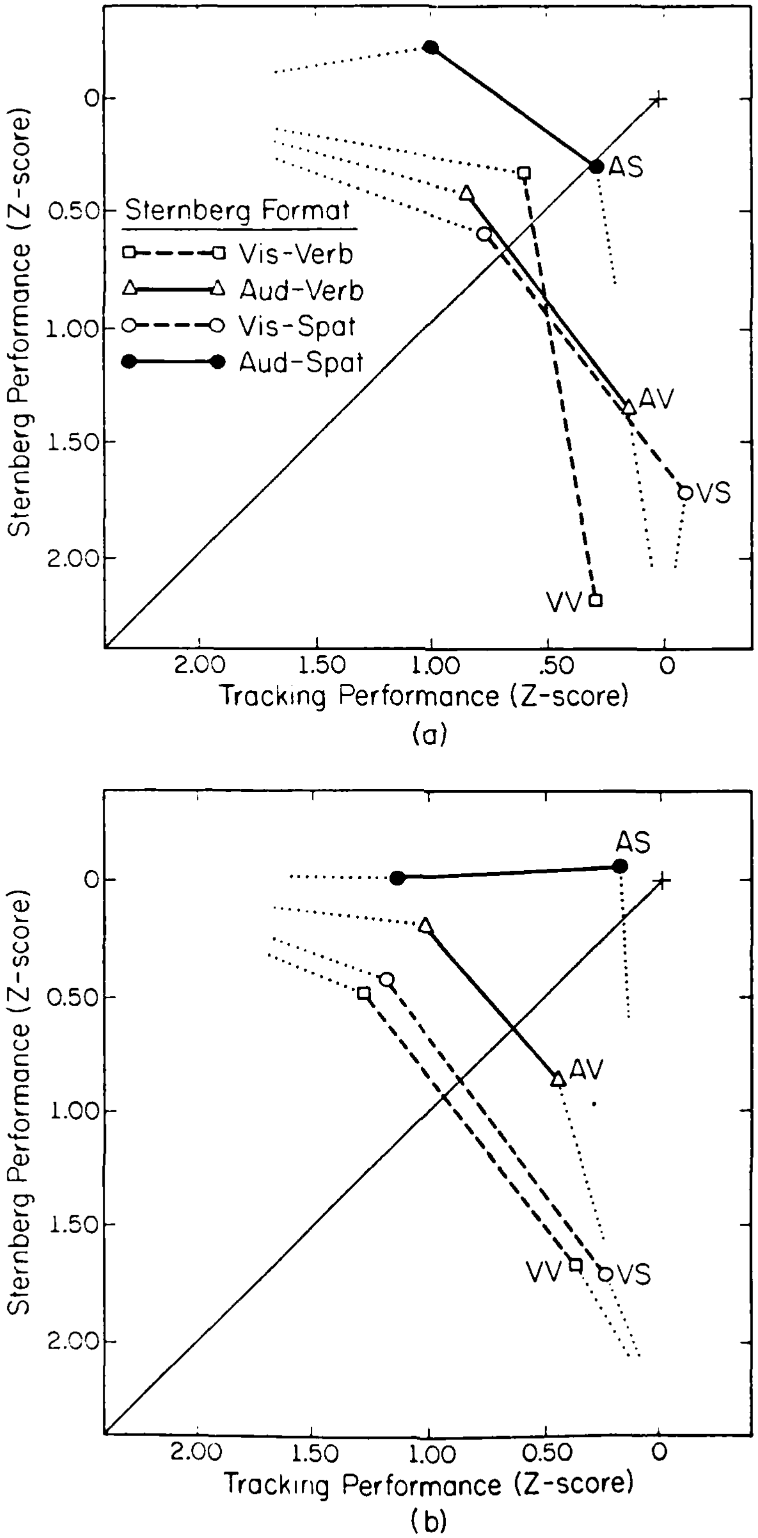

Figure 7. Performance Operating Characteristic (POC) for the four display formats and the two bias conditions: (a) perceptual strategy; (b) response strategy.

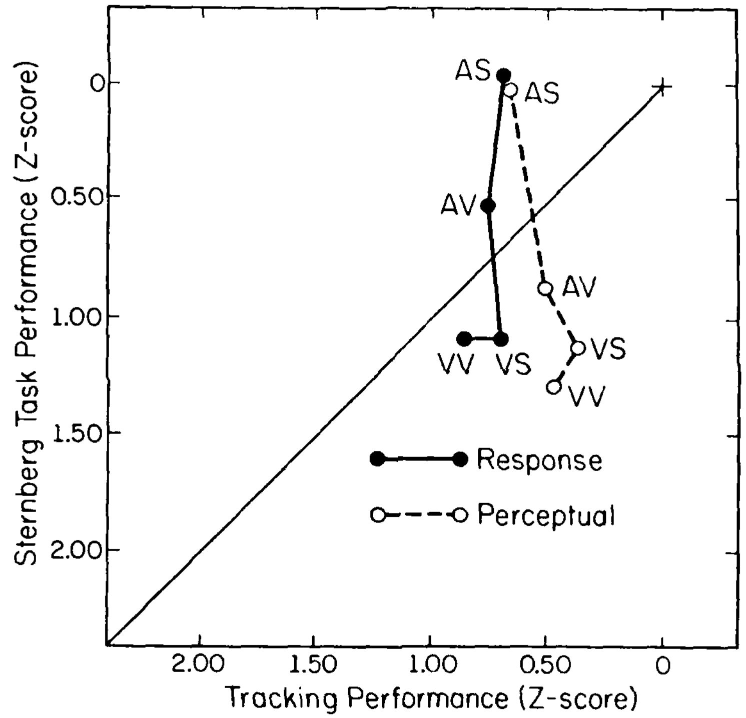

Figure 8. Performance operating characteristic representation of the four formats and two strategies averaged across the two bias conditions.

these are predicted to increase spatial interference with the spatial tracking task.

The second interesting characteristic of Figure 7 concerns the relative placement of the time-sharing efficiency plots for the two strategy conditions. While neither is clearly superior to the other (a fact reflected in the earlier analysis), it is apparent that employing the response strategy produces a bias to shift resources toward the Sternberg task, while a perceptual strategy leads to the opposite bias. This difference is consistent across the four format conditions.

Finally, Figure 9 displays the magnitude of the bias effect itself, that is, the distance between the pairs of points connected by the straight lines in Figure 7. The ordering of points across the abscissa is the order that predicts increasing shared resources between the tracking and the Sternberg task, and hence, increasing effects of priorities. For performance with the response strategy (solid line) this predicted ordering is observed. However, for performance with the perceptual strategy (dashed line), the verbal inputs (AV and VV) tend to yield greater effects of priorities than the spatial (AS and VS). In general, there appears to be little overall differences in the magnitude of the allocation effect between the two strategy conditions.

Discussion

The numerous complex results of this experiment may be roughly partitioned into those that were more or less expected and predicted on the basis of multiple resource theory, and those that were somewhat unexpected. Three major results were expected and observed:

Learned Effects

(1) For both tasks, the effect of input modalities were

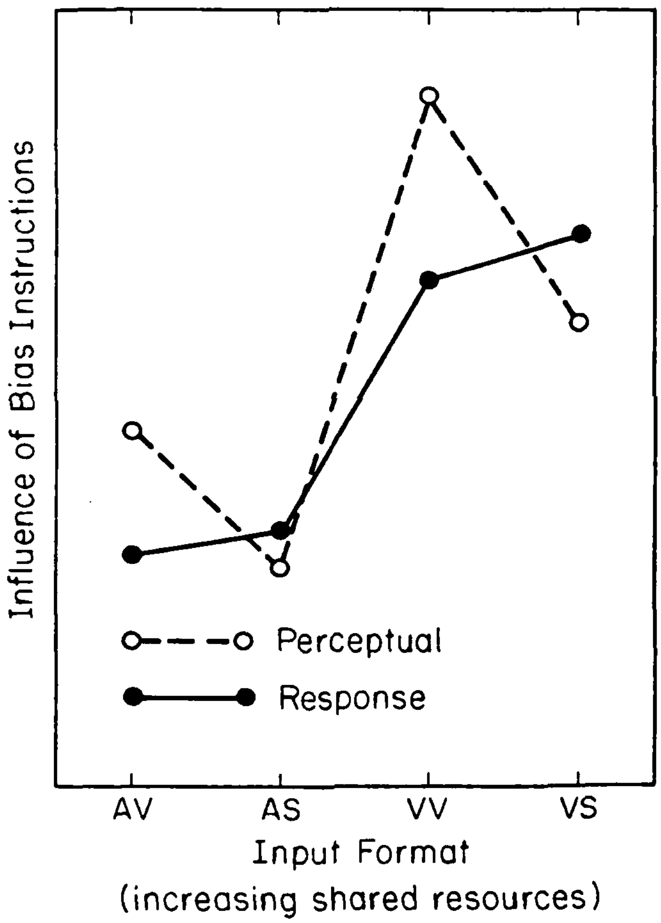

Figure 9. The effect of bias on the joint performance of both tasks, as a function of strategy and input format. The ordinate represents the separation between the two points making of each POC in Figure 7.

pronounced. The visual Sternberg task interfered more than the auditory. This effect is revealed both in the POCs of Figures 7 and 8, and in the individual data plots of Figures 2 and 3. Furthermore, the influence of task priorities was greatest when common input modalities were used, and the advantage of using separate modalities was enhanced when the response strategy was employed. The first of these priority effects is directly predicted from multiple resource theory (Vidulich & Wickens, 1981); the second will be discussed further below.

(2) Across all task configurations performance on both tasks was influenced by priority instructions. This suggests that the two tasks, despite their structural dissimilarity of processing stage and code, shared at least some resources in common--a point that will be elaborated below. As noted above, the priority effect was enhanced when the visual modality was employed for both tasks.

(3) The two strategies were learnable. Subjects were clearly able to attain equivalent levels of _performance_, by engaging in different forms of _behavior_, as the latter was induced by instruction and measured by the assessment of response velocity. The impact of these strategy differences was _not_ however quite the same as had been anticipated, and these departures from expected effects will be discussed below.

Unexpected Effects

(1) _Processing codes_. The multiple resource theory predicted that when the spatial, rather than the verbal code was employed for the Sternberg task display, three consequences should have resulted: (a) interference between tasks would increase, (b) the "strategy" effect should have been enhanced, and (c) the effect of priority instructions should have been enhanced. In fact, none of these findings were

observed, a result that indicates perhaps that the "spatial" variant of the Sternberg task was not as spatial as intended (or did not compete for common processing resources with tracking). The failure of the particular kind of stimuli used here to be processed differently from the verbal stimuli has also been observed in a study in our laboratory by Braune and Wickens (1983).

(2) Strategy effects. The effects of adopting a pe- ptual versus response strategy also were not as expected. The findings here also departed from expectations in three regards: (a) We anticipated that adopting the perceptual strategy would interfere more with the perceptual/ cognitive Sternberg task, and it did not. (b) We anticipated that adopting the perceptual strategy, by generating more shared resources between tasks, would lead to a greater effect of priorities. That is, priorities would interact with strategy. (c) We anticipated that adopting the perceptual strategy, by increasing competition for early processing resources, would increase the advantage of employing separate codes and modalities. The results indicated only marginal support for these predictions. With regard to the first prediction, Figure 8 shows a reduction in Sternberg time-sharing efficiency brought about the perceptual strategy. However, this was accompanied by an improvement in tracking performance, so the net effect of the perceptual strategy was a shift in bias away from Sternberg, toward the tracking task.

Neither of the other two anticipated bias effects were realized. Priorities did not interact with strategies (as indicated in the ANOVAs and in Figure 9), and there was no added advantage of using separate display formats when the perceptual strategy was used (see Figure 8). In fact, as noted previously, the advantage of using different

modalities of input was only realized when the response and <u>not</u> the perceptual strategy was in force.

There are two possible explanations for these coherent departures from expectations. One related to the nature of the strategy manipulations, and the other to the nature of the processing resources themselves. On the one hand, it is possible that the terms "perceptual" and "response" do not actually describe the nature of the imposed loads. Thus, on the one hand, the "perceptual" strategy, although requiring perception of higher derivatives, also forced subjects to generate continuous, controlled, analog responses, with a high level of precision. On the other hand, the "bang-bang" strategy may be thought to leave the response component relatively simple with no analog precision. What is required in carrying out such a strategy is a valid internal cognitive model of the system dynamics that forms the basis for deciding when control reversals should optimally be implemented (Gill et al., 1982; Hess, 1979). Thus, the "load" of the bang-bang strategy may be conceived as most heavy on the operation of the internal model in working memory--an "early" processing resource in the multiple resource model. If this interpretation is accepted, and the names applied to the two strategies should be reversed, then the advantge of the auditory modality with the bang-bang strategy can be readily understood.

The second alternative possibility relates to the concept of <u>general resources</u>. The multiple resource model proposes that the different processing structures (stages, codes, modalities) each possess their own <u>exclusive</u> supply of resources. However, this view is also consistent with the assumption that there exists a general pool of <u>sharable</u> resources across all stages, modalities, and codes which can

be used to supplement the specific resources as task demands require (Wickens, 1980; 1984b). It is these resources that are competed for by the tracking and Sternberg tasks, and prevent the two tasks, otherwise quite different in their processing structures, from being perfectly time-shared. It is these resources also that lead to the "allocation effect" of bias, even in the case of minimum resource overlap. According to this hypothesis then, the consequence of adopting the "perceptual" lead-generating strategy is to induce the subject to shift the general resources to the "early" processing stages, thereby providing sufficient resources to process the two tasks, independently of their processing modalities and codes. On the other hand, adopting a bang-bang response strategy makes resources scarce for perceptual and central processing, as these general resources are shifted toward the late processing stage in order to coordinate the timing of the response. As a result, with the bang-bang strategy, since there are fewer resources available for perception, it becomes more critical that task demands are distributed across display formats, and so the auditory modality assists performance.

From the present data, it is impossible to determine which of these two hypotheses may be the correct one. Neither were anticipated, yet both are supported by different aspects of the data, and are consistent with theoretical assumptions made independently from this particular experiment (i.e., Hess's model of processing in higher order control, and the assumptions of general capacity).

Two strong conclusions can be drawn concerning the applied implications of this research to the topic of secondary task workload measurement in flight tasks. We have described elsewhere the importance of workload measurement indices be <u>sensitive</u>--that is, that

they reflect changes in task difficulty when such changes are known to exist. In the current data we have manipulated task difficulty by increasing control order. The priority conditions in which the tracking task is emphasized approximates that typical of the "secondary task paradigm." These are the points to the right and bottom of Figure 7a and b. In a sense the optimum secondary task formats here would be those for which the change in reaction time from first to second order control (the size of the Sternberg decrement) is largest, while the tracking decrements are smallest. Across both strategy conditions it is clear that the visual conditions meet the former criterion far better than do the auditory, while the second is met by both. Hence, the conclusion from these data is consistent with one we have drawn elsewhere: that the optimum secondary tasks should share resources with the primary.

In conclusion, the relations between strategy, performance, and processing resources is one that clearly is in need of further investigation; so also is the distinction between the strategy of performing a single task (as here the contrast between lead and bang-bang strategy), and between strategies of dual task resource allocation (the distinction between mobilizing general resources to early vs. late processing stages). The present data suggest that these effects could have important implications for how workload is measured by secondary task techniques, as well as for the success of time-sharing between manual control and discrete activities.

Appendix A

The following instructional procedure was employed to train subjects in using the two strategies. Subjects were first allowed to practice tracking with first order tracking dynamics and .32 degree frequency disturbance in order to acquaint them with the display and the control stick as well as acquaint them with first order control dynamics. After two three-minute practice trials, the experimenter came into the booth and explained second order tracking, and the two strategies. Instructions were as follows:

You have just performed what is called a first order tracking task which is relatively easy. During the next series of trials you will engage in a more difficult form of tracking called second order. This is more like the task of flying an aircraft. Second order tasks are difficult because they are both sluggish and unstable. If your cursor shows an error as in Figure A1, and you want to bring that error down to zero in the center, if you put your stick hard to the right, the cursor will gradually accelerate to the right (as in the top half of the figure). By the time it reaches the center it will be going so fast that if you reverse the stick to "apply the brakes" you will overshoot (as in the bottom half of the figure). Try one trial and see what I mean (subject is given a second order trial with 0 degree frequency disturbance).

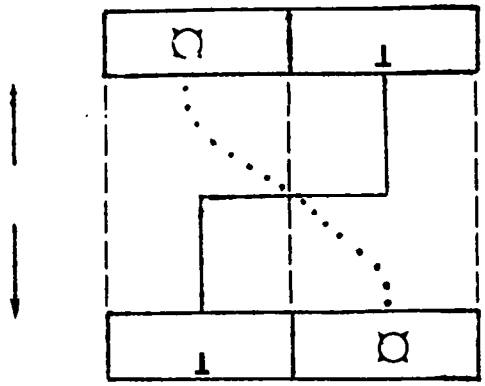

Figure A1. Example of second-order tracking (square signifies cursor and the solid line represents the direction of the control stick deflection). If the controller waits until the cursor reaches the midline to reverse input, the cursor will overshoot.

Now, there are two "styles" or "strategies" of coping with second order tracking. The first we will call a response-strategy. Here, if you perceive a large error, your goal is to reduce it as soon as you can. This means that you will move the stick all the way to the stop as rapidly as possible to get a maximum acceleration (as in Figure A2). Of course, to avoid overshooting as we saw before, you must "apply the brakes" and reverse the stick to the other side well before you reach the centerline.

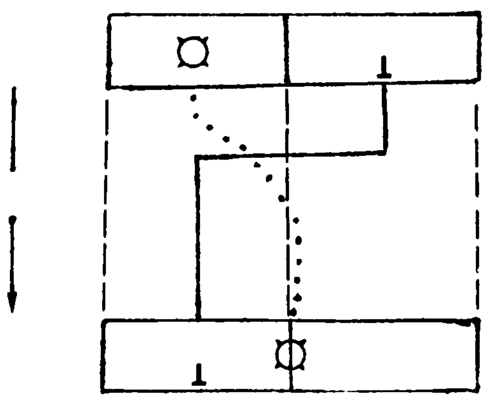

Figure A2. Example of second-order tracking with response strategy. Note the large, rapid stick deflections.

Ideally, this will reduce your error as rapidly as possible which is good. However, there are two potential costs associated with the response strategy which, if you were the pilot of an actual aircraft, you might wish to avoid. On the one hand, by putting on maximum acceleration and maximum brakes you are in danger of overshooting. If you were a pilot in such an aircraft, the violent movement might be

unpleasant to your passengers. On the other hand, full control movement would lead to the unnecessary waste of fuel. Thus, an alternative strategy which is both more economical and leads to a "smoother ride" is a perceptual strategy. Here your goal is to anticipate where the error signal is going to be in the future, by continuously determining how fast and in what direction it is going in the present, and moving the control stick smoothly to counteract its momentary speed (see Figure A3). This will require you to pay relatively closer attention to perceiving the speed of the error and make smoother control movements. Hence, we call this perceptual strategy.

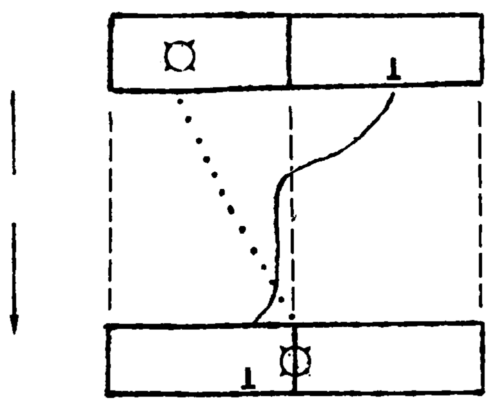

Figure A3. Example of second-order tracking with the perceptual strategy. Note the rather constant velocity of the target and the relatively small stick deflections.

You should note that tracking can be performed effectively using either strategy, and that you will probably naturally choose some combination of both. However, on the following trials I would like you to try to emphasize either one or the other strategy, depending upon which I tell you. Remember, in the response strategy your primary goal is to correct errors as soon as they appear, by full stick deflections. In the perceptual strategy you are equally concerned with keeping your error as small as possible, but to do this you need to respond continuously and smoothly to the perceived error velocity. Do you have any questions?

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